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## Probing in-medium spin–orbit interaction with intermediate-energy heavy-ion collisions

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## ABSTRACT

Incorporating for the first time both the spin and isospin degrees of freedom explicitly in transport model simulations of intermediate-energy heavy-ion collisions, we observe that a local spin polarization appears during collision process. Most interestingly, it is found that the nucleon spin up–down differential transverse flow is a sensitive probe of the spin–orbit interaction, providing a novel approach to probe both the density and isospin dependence of the in-medium spin–orbit coupling that is important for understanding the structure of rare isotopes and synthesis of superheavy elements.

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The spin–orbit coupling is common to the motion of many objects in nature from quarks, nucleons, and electrons to planets and stars. In nuclear physics, it has been very well known for a long time that the spin–orbit coupling is crucial for understanding the structure of finite nuclei, such as the magic numbers [1,2]. However, many interesting questions regarding the in-medium spin–orbit coupling, especially its density and isospin dependence, remain unresolved although in free space it has been well determined from nucleon–nucleon (NN) scattering data [3]. Indeed, several phenomena observed or predicted in studying properties of nuclear structures have been providing us some useful information about the in-medium spin–orbit interaction. For instance, the kink of the charge radii of lead isotopes can only be explained by introducing a weakly isospin-dependent spin–orbit coupling [4,5]. Moreover, strong experimental evidences of a decreasing spin–orbit coupling strength with increasing neutron excess were reported [6,7]. Furthermore, new experiments are currently being carried out at several laboratories to explore the density and isospin dependence of the spin–orbit coupling by comparing energy splittings of certain orbits in the so-called “bubble” nuclei [8,9] with those in normal nuclei [10]. The knowledge of the in-medium spin–orbit interaction is useful for understanding properties of drip-line nuclei [11], the astrophysical r-process [12], and the location of stability island for superheavy elements [13,14].

While effects of the spin–orbit interaction on nuclear structure have been studied extensively, very little is known about its effects in heavy-ion collisions. Within the time-dependent Hartree–Fock (TDHF) calculations the nucleon spin–orbit interaction was found to affect the fusion threshold energy [15] and lead to a local spin polarization [16,17]. In non-central relativistic heavy-ion collisions at 200 GeV/nucleon the partonic spin–orbit coupling was found to lead to a global quark spin polarization [18]. However, to our best knowledge, no study on effects of the spin–orbit interaction in intermediate-energy heavy-ion collisions has been carried out yet. On the other hand, several facilities for spin-polarized beams have been developed for about twenty years. It has already been shown that spin-polarized projectile fragments in peripheral collisions are measurable through the angular distribution of  $\gamma$  or  $\beta$  decays at both GSI and RIKEN [19,20]. In addition, at AGS and RHIC energies, people can already obtain the spin-flip probability and distinguish spin-up and spin-down nucleons in elastic pp or pA collisions by measuring the analyzing power [21]. One thus expects that spin-related experimental observables in intermediate-energy heavy-ion collisions can be measured in the near future, if they are indeed helpful for enriching our knowledge about the poorly known in-medium spin–orbit interaction. In this Letter, within a newly developed spin–isospin dependent transport model, we show that the nucleon spin up–down differential transverse flow in heavy-ion collisions at intermediate energies is a sensitive probe of the density and isospin dependence of the in-medium nucleon spin–orbit interaction.

Starting from the following effective nucleon spin–orbit interaction [22]

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$$V_{so} = iW_0(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{k} \times \delta(\vec{r}_1 - \vec{r}_2)\vec{k}', \quad (1)$$

where  $W_0$  is the strength of the spin-orbit coupling,  $\vec{\sigma}_{1(2)}$  is the Pauli matrix,  $\vec{k} = (\vec{p}_1 - \vec{p}_2)/2$  is the relative momentum operator acting on the right with  $\vec{p} = -i\nabla$ , and  $\vec{k}'$  is the complex conjugate of  $\vec{k}$ , the single-particle Hamiltonian in nuclear matter can be written as

$$h_q = \frac{p^2}{2m} + U_q + U_q^s + U_q^{so} \quad (2)$$

where  $q = n$  or  $p$ ,  $U_q$  and  $U_q^s$  are the central bulk and spin potential, respectively, and  $U_q^{so}$  is the spin-orbit potential. In this work, we use a momentum-independent  $U_q$  leading to an incompressibility of  $K_0 = 230$  MeV for symmetric nuclear matter, a symmetry energy  $E_{sym} = 30$  MeV and its density slope  $L = 60$  MeV at saturation density  $\rho_0 = 0.16 \text{ fm}^{-3}$  similar to the parameterization of a modified Skyrme-like interaction [23]. The  $U_q^s$  and  $U_q^{so}$  can be expressed respectively as,

$$U_q^s = -\frac{W_0}{2}[\nabla \cdot (\vec{j} + \vec{j}_q)] - \frac{W_0}{2}\vec{p} \cdot [\nabla \times (\vec{s} + \vec{s}_q)] - \frac{W_0}{2}\vec{\sigma} \cdot [\nabla \times (\vec{j} + \vec{j}_q)], \quad (3)$$

$$U_q^{so} = \frac{W_0}{2}(\nabla \rho + \nabla \rho_q) \cdot (\vec{p} \times \vec{\sigma}), \quad (4)$$

where  $\vec{j}$ ,  $\vec{s}$ ,  $\vec{j}$ , and  $\rho$  are the nucleon spin-current, spin, momentum, and number densities, respectively. We notice here that the second and third terms in Eq. (3) are the time-odd contributions [24] suppressing the first term in Eq. (3) and the term in Eq. (4), respectively, and neglecting them would break the Galilean invariance and induce a spurious spin excitation [16]. Taking into account both the density [25] and isospin dependence [4] of the spin-orbit interaction, the  $U_q^s$  and  $U_q^{so}$  can be generally written as

$$U_q^s = -\frac{W_0^*(\rho)}{2}[\nabla \cdot (a\vec{j}_q + b\vec{j}_{q'})] - \frac{W_0^*(\rho)}{2}\vec{p} \cdot [\nabla \times (a\vec{s}_q + b\vec{s}_{q'})] - \frac{W_0^*(\rho)}{2}\vec{\sigma} \cdot [\nabla \times (a\vec{j}_q + b\vec{j}_{q'})], \quad (5)$$

$$U_q^{so} = \frac{W_0^*(\rho)}{2}(a\nabla \rho_q + b\nabla \rho_{q'}) \cdot (\vec{p} \times \vec{\sigma}) \quad (q \neq q'). \quad (6)$$

In the above,  $W_0^*(\rho) = W_0(\rho/\rho_0)^\gamma$  represents the density-dependence of the spin-orbit coupling. Different combinations of  $\gamma$ ,  $a$ , and  $b$  can be used to mimic various density and isospin dependences of the in-medium spin-orbit interaction while preserving the Galilean invariance. We notice that with  $\gamma = 0$ ,  $a = 2$ , and  $b = 1$  Eqs. (5) and (6) reduce to Eqs. (3) and (4), while equal values for  $a$  and  $b$ , and a nonzero value for  $\gamma$  were predicted within a relativistic mean-field model [5]. Neglecting the density dependence of  $W_0^*$ , the spin-orbit coupling constant  $W_0$  ranges from about 80 MeV fm<sup>5</sup> to 150 MeV fm<sup>5</sup> [26–28], while the values of  $\gamma$ ,  $a$ , and  $b$  are still under hot debate.

To model the spin-isospin dynamics in heavy-ion collisions at intermediate energies, we incorporate explicitly the spin degree of freedom and the spin-related potentials in a previously developed isospin-dependent Boltzmann–Uehling–Uhlenbeck (BUU) transport model, see, e.g., Refs. [29,30]. The new model is dubbed SI-BUU12. To our best knowledge, the spin degree of freedom was never considered before in any of the existing transport models for heavy-ion reactions at intermediate energies since the emphasis of the community has been on extracting information about the Equation of State (EOS) of symmetric nuclear matter, density dependence of nuclear symmetry energy, and in-medium NN scattering cross

sections using spin-averaged experimental observables. In the SI-BUU12 model,  $\rho$ ,  $\vec{s}$ ,  $\vec{j}$ , and  $\vec{j}$  are all calculated by using the test particle method [31,32]. The equations of motion in the presence of the spin-orbit interaction are

$$\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m} + \frac{W_0^*(\rho)}{2}\vec{\sigma} \times (a\nabla \rho_q + b\nabla \rho_{q'}) - \frac{W_0^*(\rho)}{2}\nabla \times (a\vec{s}_q + b\vec{s}_{q'}), \quad (7)$$

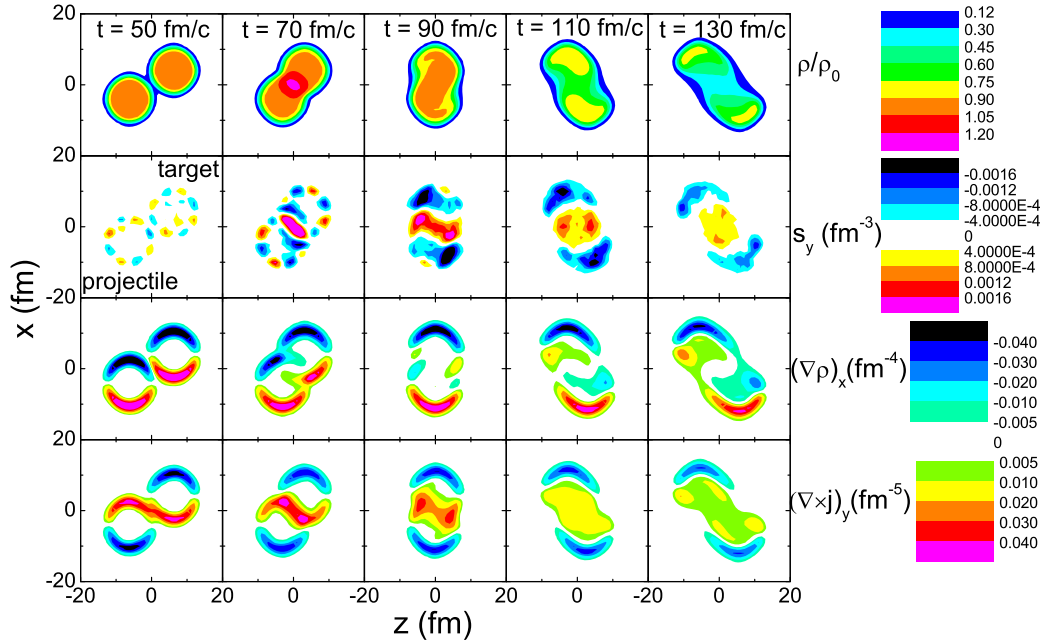
$$\frac{d\vec{p}}{dt} = -\nabla U_q - \nabla U_q^s - \nabla U_q^{so}, \quad (8)$$

$$\frac{d\vec{\sigma}}{dt} = W_0^*(\rho)[(a\nabla \rho_q + b\nabla \rho_{q'}) \times \vec{p}] \times \vec{\sigma} - W_0^*(\rho)[\nabla \times (a\vec{j}_q + b\vec{j}_{q'})] \times \vec{\sigma}. \quad (9)$$

In the center-of-mass frame of nucleus–nucleus collisions, two Fermi spheres of projectile/target nucleons are Lorentz boosted in the  $\pm z$  direction. Note that the  $U_q^{so}$  and the last term in  $U_q^s$  are most important among the spin-related potentials, with the former being the time-even contribution while the latter being the time-odd contribution. During the collision process, the density gradient  $\nabla \rho$  points mainly along the impact parameter of the reaction, i.e., the  $x$  axis, while the momentum density  $\vec{j}$  is mainly located in the reaction plane ( $x$ – $o$ – $z$ ) and  $\nabla \times \vec{j}$  is thus along the  $y$  axis perpendicular to the reaction plane. Due to the spin-orbit potential, the nucleon spin  $\vec{\sigma}$  tends to be parallel to the direction of  $\vec{p} \times \nabla \rho$  in order to lower the energy of the system. On the other hand, the time-odd contribution makes the nucleon spin  $\vec{\sigma}$  parallel to  $\nabla \times \vec{j}$ , which is in the opposite direction of  $\vec{p} \times \nabla \rho$  [16]. The result of their competition determines the final direction of the nucleon spin. We will refer in the following a nucleon with its spin in the  $+y$  ( $-y$ ) direction as a spin-up (spin-down) nucleon. During heavy-ion collisions at intermediate energies with different combinations of targets, projectiles, and impact parameters, dynamical systems of nucleons with different density gradients, momentum currents, and the isospin asymmetries are formed. These reactions thus provide a useful tool for investigating the density and isospin dependence of nucleon spin-orbit coupling. Of course, to realize this goal the first challenge is to find sensitive experimental observables. Transport models have been very successful in both extracting reliable information about the nuclear EOS and predicting new phenomenon that have later been experimentally confirmed, see, e.g., Refs. [30,33]. We are confident that the SI-BUU12 model has similar predictive powers for studying spin physics with intermediate-energy heavy-ion collisions.

Nucleon–nucleus scattering experiments have shown that nucleons may flip their spins after NN scatterings due to spin-related nuclear interactions, see, e.g., Ref. [34] for a review. Although not well determined yet, the spin-flip probability for in-medium NN scatterings is known to be appreciable, depending on the collision energy and the momentum transfer [35]. In the present work we will test different options of setting spins, including randomizing, flipping, or keeping spins unchanged after each NN scattering to study effects of different spin-flip probabilities on spin-sensitive observables. In addition, a spin- and isospin-dependent Pauli blocking is introduced in the SI-BUU12 model.

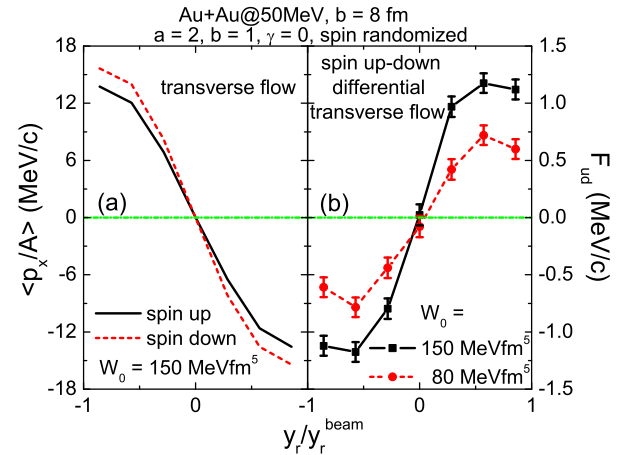
As an illustration of the effects from spin-orbit coupling, it is interesting to first examine for a typical reaction at intermediate energies the time evolution of the  $y$  component of the spin density  $s_y$ , the  $x$  component of the density gradient  $(\nabla \rho)_x$ , and the  $y$  component of the curl of the momentum density  $(\nabla \times \vec{j})_y$  in comparison with the nucleon density contour in the reaction plane. Shown in Fig. 1 are these quantities for Au + Au collisions at a beam energy of 50 MeV/nucleon and an impact parameter



**Fig. 1.** (Color online.) Contours of nucleon reduced density  $\rho/\rho_0$  (first row),  $y$  component of spin density  $s_y$  (second row),  $x$  component of the density gradient  $(\nabla\rho)_x$  (third row), and  $y$  component of the curl of the momentum density  $(\nabla\times\vec{j})_y$  (fourth row) in the reaction plane at different stages in Au + Au collisions at a beam energy of 50 MeV/nucleon and an impact parameter of  $b=8$  fm.

of  $b=8$  fm. For this example, we set  $W_0 = 150 \text{ MeVfm}^5$ ,  $\gamma = 0$ ,  $a = 2$ ,  $b = 1$ , and the spins of the colliding nuclei are randomized after each scattering. Initially we put the projectile and target nuclei without spin polarization far away, and there is no spin polarization before they physically meet each other due to the cancelation of the time-even and time-odd contributions. During the collision process, a local spin polarization appears as was first observed in TDHF calculations [16,17]. It is clearly seen that the spins of participant and spectator nucleons are more likely to be up and down, respectively, in the most compressed stage of the reaction. The spin polarization follows the direction of the vector  $\nabla\times\vec{j}$  rather than that of  $\vec{p}\times\nabla\rho$  since the latter has a smaller magnitude although it points to the opposite direction of the former. In the later stage, however, the spin polarization becomes weaker because of NN scatterings and other spin mixing effects, especially for participant nucleons in the high-density region.

As shown in the equations of motion, the spin-orbit coupling also affects the nucleon momentum and spatial distributions besides the spin polarization. Nucleon transverse collective flow, measured by using the average transverse momentum  $\langle p_x(y_r) \rangle$  in the reaction plane versus rapidity  $y_r$ , is one of the best known observable for revealing effects of density gradients in nuclear reactions [32,33,36]. Since spin-up and spin-down nucleons with the same momentum experienced opposite spin-related potentials during the whole collision process, we expect the difference in transverse flow of spin-up and spin-down nucleons to be sensitive to the spin-orbit coupling while other effects will be largely canceled out. To test this idea, we first compare in the left panel of Fig. 2 the transverse flows of spin-up and spin-down nucleons. It is seen that the transverse flow of spin-up nucleons is smaller than that of spin-down ones. This can be understood by looking at the  $x$  component of the density gradient and the  $y$  component of the curl of the momentum density shown in the third and the fourth rows of Fig. 1. By examining the time evolution, we found that the effects of the spin-orbit interaction on the transverse flow during the first 40 fm/c of the collision are mostly washed out due to violent interactions. The spin-dependent transverse flow is mainly

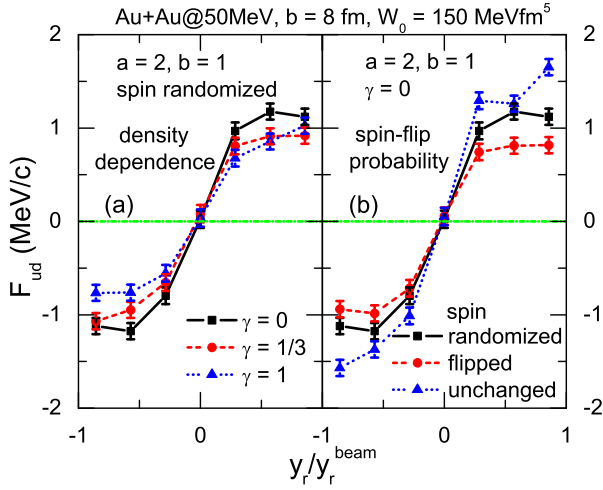


**Fig. 2.** (Color online.) Transverse flow of spin-up nucleons and spin-down nucleons (a) and spin up-down differential flows using different  $W_0$  (b) for the same reaction as in Fig. 1.

determined by the dynamics afterwards. As the projectile (target) is still moving in the  $+z$  ( $-z$ ) direction, the participant nucleons from the projectile (target) with negative (positive)  $(\nabla\rho)_x$  give a more repulsive/attractive spin-orbit potential  $[\nabla\rho\cdot(\vec{p}\times\vec{\sigma}) > / < 0]$  for spin-up/down nucleons. This leads to a larger transverse flow for spin-up nucleons than spin-down ones. On the other hand, the time-odd term contributes exactly in the opposite direction and is stronger than the time-even term. The combined effects therefore lead to a smaller (larger) transverse flow for spin-up (spin-down) nucleons.

To extract more accurately information about the spin-related potentials without much hinderance of spin-independent potentials, we investigate next the spin up-down differential transverse flow

$$F_{ud}(y_r) = \frac{1}{N(y_r)} \sum_{i=1}^{N(y_r)} \sigma_i(p_x)_i, \quad (10)$$

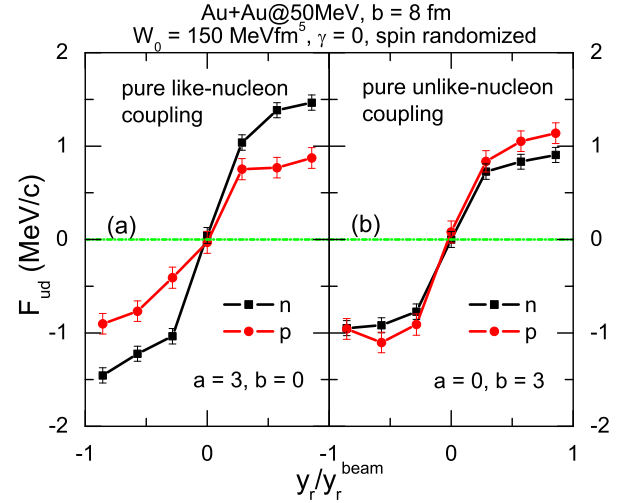


**Fig. 3.** (Color online.) Spin up-down differential transverse flows using different density dependence of the spin-orbit coupling coefficients (a) and different treatments of spin after NN scatterings (b) for the same reaction as in Fig. 1.

where  $N(y_r)$  is the number of nucleons with rapidity  $y_r$ , and  $\sigma_i$  is 1 (−1) for spin-up (spin-down) nucleons. Similar to the neutron–proton differential transverse flow for probing the symmetry potential [37], the spin up-down differential transverse flow maximizes the effects of the opposite spin-related potentials for spin-up and spin-down nucleons while canceling out largely spin-independent contributions. Indeed, the spin up-down transverse flow is a sensitive probe of the spin-orbit coupling strength  $W_0$ . As an example, shown in the right panel of Fig. 2 is a comparison of the spin up-down differential transverse flows obtained using the two limiting values of  $W_0$  used in the literature. To be conservative, in this example we have used the randomized spin assignment after each NN scattering which is the worst scenario for revealing effects of the spin-orbit potential. Fortunately, even in this case, a 47% increase in  $W_0$  leads to an approximately 40% higher up-down differential flow far beyond the statistical errors in the calculation.

The density dependence of the spin-orbit coupling, which was tested earlier, see, e.g., Ref. [25], is still almost completely unknown, and this has recently motivated more new experiments [10]. To investigate effects of the density dependence of the spin-orbit coupling on the spin up-down differential flow, shown in panel (a) of Fig. 3 are the results obtained by varying only the  $\gamma$  parameter. It is seen that the spin up-down differential flow is larger for a weaker density dependence of the spin-orbit coupling if its strength at saturation density is fixed.

The isospin dependence of the spin-orbit coupling is another interesting issue especially relevant for understanding the structure of rare isotopes and the synthesis of superheavy elements. To evaluate potential applications of our approach in further constraining the isospin dependence of the spin-orbit interaction, we next compare the spin up-down differential flows for neutrons and protons using the pure like-nucleon coupling ( $a = 3$  and  $b = 0$ ) and pure unlike-nucleon coupling ( $a = 0$  and  $b = 3$ ) in panel (a) and panel (b) of Fig. 4, respectively. As the system considered is globally neutron-rich and  $\nabla \rho_n$  and  $\nabla \times \vec{j}_n$  are generally larger than  $\nabla \rho_p$  and  $\nabla \times \vec{j}_p$ , respectively, the pure like (unlike)-nucleon coupling leads to an appreciably larger (smaller) spin up-down differential flow for neutrons than for protons. Moreover, the unlike-nucleon coupling generally reduces slightly the overall strength of the spin-related potentials and thus the spin up-down differential flow. Of course, more neutron-rich systems will be better for



**Fig. 4.** (Color online.) Spin up-down differential transverse flows for neutrons and protons from pure like-nucleon coupling (a) and pure unlike-nucleon coupling (b) for the same reaction as in Fig. 1.

probing the isospin dependence of the spin-orbit coupling using the double differential flow between spin up-down neutrons and protons.

Finally, what are the effects of the possible spin flip in NN scatterings on the spin up-down differential flow? We answer this question quantitatively by using the results shown in the right panel of Fig. 3. Due to the lack of knowledge about the energy and isospin dependence of the spin-flip probability for in-medium nucleon–nucleon scatterings, we compare results obtained by using the following three choices for setting the final spins of colliding nucleons after each NN scattering: (1) flipped, (2) randomized, or (3) unchanged, effectively varying the spin-flip probability from large to small. It is seen that the spin up-down differential transverse flow decreases with increasing spin-flip probability as one expects. Moreover, it is very encouraging to see that the spin up-down differential flow is still considerable even if a 100% spin-flip probability is assumed, further proving the validity of using it as a probe of the spin-orbit coupling.

In summary, the spin degree of freedom and the spin-related potentials are incorporated for the first time in an isospin-dependent transport model providing a useful new tool for investigating the spin-isospin dynamics of heavy-ion collisions at intermediate energies, such as the development of local spin polarization in these reactions. The nucleon spin up-down differential transverse flow is shown to be a sensitive probe of the in-medium spin-orbit interaction. Comparisons with future experiments will allow us to determine the density and isospin dependence of the in-medium spin-orbit coupling that has significant ramifications in both nuclear physics and astrophysics.

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